

Shocked ammonia in the WR nebula NGC 2359

J. R. Rizzo¹, J. Martín-Pintado

Observatorio Astronómico Nacional, Aptdo. Correos 1143, 28800 Alcalá de Henares, Spain

jrizzo@oan.es, martin@oan.es

and

C. Henkel

Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, 53121 Bonn, Germany

p220hen@mpifr-bonn.mpg.de

ABSTRACT

We report the detection of the (1,1) and (2,2) metastable lines of ammonia (NH_3) in the molecular cloud associated with the Wolf-Rayet (WR) nebula NGC 2359. Besides the CO and H_2 , this is the first molecule detected in the environs of a WR star. Width ($\Delta V_{1/2} = 3 \text{ km s}^{-1}$) and radial velocity ($V_{\text{LSR}} \sim 54 \text{ km s}^{-1}$) indicate that the NH_3 lines arise from the molecular cloud which is interacting with the WR star. The rotational temperature derived from the (1,1) and (2,2) line intensity ratios is about 30 K, significantly larger than the typical kinetic temperature of the ambient gas of $\sim 10 \text{ K}$. The derived NH_3 abundance is $\sim 10^{-8}$. Linewidth, abundance and kinetic temperature can be explained if NH_3 is released from dust grain mantles to the gas phase by shocks produced by the expansion of the bubble created by the WR stellar wind. We briefly discuss the implications of the detection of warm NH_3 associated with a WR star in connection to the hot NH_3 emission detected in the Galactic Center and in the nuclei of external galaxies.

Subject headings: ISM: abundances — ISM: individual (NGC 2359) — ISM: molecules — Stars: individual (HD 56925) — Stars: Wolf-Rayet

1. Introduction

The interstellar medium surrounding Wolf-Rayet (WR) stars is expected to be strongly disturbed by the fast stellar evolution with rapidly varying mass loss rates, luminosities, and elemental composition of the ejecta. The Wolf-Rayet (WR) star HD 56925 –WR 7 in the catalogue of van der Hucht (2001)– excites the wind-blown bubble NGC 2359 (Chu, Treffers & Kwitter 1983). The chemical enrichment (Esteban et al. 1990), the nearly spherical morphology and the kinematics of NGC 2359 suggest a relatively recent origin for this nebula, probably produced in the WR stage of the exciting star. The HII region

which surrounds the wind-blown bubble seems to be confined by molecular material in the southern direction (Schneps et al. 1981). The spatial distribution of the 1–0 (1) line of H_2 (St-Louis et al. 1998) suggests that the H_2 vibrationally excited emission is produced by the interaction of the WR star with the molecular material.

Recently Rizzo, Martín-Pintado & Mangum (2001, paper I) have mapped the CO $J = 1 \rightarrow 0$ and $J = 2 \rightarrow 1$, and the ^{13}CO $J = 1 \rightarrow 0$ emission over the whole nebula. They found that the two velocity components toward the southern part of the nebula have LSR radial velocities (V_{LSR}) of 54 and 67 km s^{-1} . The 67 km s^{-1} component has a narrow linewidth (1 km s^{-1}) indicating that this component traces quiescent material. On the other hand, the component with V_{LSR} of 54 km

¹On leave of absence from Instituto Argentino de Radioastronomía, Argentina

s^{-1} is broad (5 km s^{-1}), surrounds the southern and eastern parts of NGC 2359 (see Fig. 1a), and is spatially anticorrelated with the narrow component. The broad linewidths and the spatial distribution of the 54 km s^{-1} component indicate that it is affected by the interaction of the WR star with the ambient material at 67 km s^{-1} . The shocks produced by the expansion of the stellar wind bubble are likely the origin of the line broadening.

Molecular chemistry can be an important tool to firmly establish if the molecular material in the broad component is affected by the strong shocks produced by the stellar wind from HD 56925. In particular, the ammonia (NH_3) fractional abundance changes from 10^{-10} in photodissociation regions to 10^{-6} in shocked regions. This is due to the fact that the NH_3 is a very fragile molecule, easily photodissociated by UV radiation (van Dishoeck 1988; Roberge et al. 1991), but it can also be released from icy grain mantles by shocks with moderate velocities (Flower & Pineau-Des-Forets 1994). In this letter we report the first detection of ammonia emission towards a WR nebula. The rather high abundance of NH_3 and the kinetic temperature found in the broad velocity component is in agreement with the idea that the molecular gas has been shocked by the stellar wind from the WR star HD 56925.

2. Observations and results

The (1,1) and (2,2) metastable ammonia lines were observed using the Effelsberg 100-m radiotelescope of the MPIfR in December 2000 and March 2001. The half power beam width of the telescope at the rest frequency of the NH_3 lines, 23.7 GHz, was $40''$. We used the new cooled dual channel HEMT K-band receiver with a typical system temperature of 230 K on a main beam brightness temperature scale. An 8192-channel autocorrelator was used as the backend. Both ammonia lines were observed simultaneously with a total bandwidth of 20 MHz and a velocity resolution of 0.06 km s^{-1} . In order to improve the S/N ratio, the spectra were later smoothed to a resolution of 0.5 km s^{-1} . The observations were made in a dual beam switching mode (switching frequency 1 Hz) with a beam throw of $121''$ in azimuth. Pointing was regularly checked and it was found to be

within $5''$. The data were calibrated using the continuum emission of NGC 7027 as the principal calibrator, assuming a flux density of 5.4 Jy at 23.9 GHz (Ott et al. 1994). Orion-KL (Hermesen et al. 1988) was used as a line calibrator. Both calibrations agree to within 10% and we conclude that line intensities on a main beam temperature scale are accurate to within $\pm 15\%$.

Figure 1a shows the spatial distribution of the $^{12}\text{CO } J = 2 \rightarrow 1$ emission of the broad component at $V_{\text{LSR}} = 53 \text{ km s}^{-1}$ in NGC 2359, overlaid on an optical image of the WR nebula. The filled square indicates the location of the maximum CO emission, which is also the position where the NH_3 data were taken. Figs. 1b to 1e show the line profiles of the $J = 1 \rightarrow 0$ lines of ^{12}CO and ^{13}CO , and the (1,1) and (2,2) lines of NH_3 , respectively. All the lines were measured with similar beam sizes of $40''$ – $50''$. Both ammonia lines are weak but clearly detected at a 7–8 σ levels. The observational parameters of the lines have been derived from gaussian fits to the profiles of the (1,1) and (2,2) lines, and the results are shown in Table 1. The radial velocities and linewidths are in good agreement with those of the broad CO component at 53 – 54 km s^{-1} , indicating that both CO and NH_3 emission arises from the same region.

Table 1: Observational and physical parameters

Parameter	Value
RA, Dec (B1950)	$07^{\text{h}}16^{\text{m}}19^{\text{s}}, -13^{\circ}11'26''$
NH_3 (1,1) fit:	
Peak emperature	$53 \pm 6 \text{ mK}$
LSR velocity	$53.1 \pm 0.6 \text{ km s}^{-1}$
Width profile	$2.6 \pm 0.6 \text{ km s}^{-1}$
NH_3 (2,2) fit:	
Peak emperature	$46 \pm 7 \text{ mK}$
LSR velocity	$53.6 \pm 0.6 \text{ km s}^{-1}$
Width profile	$3.0 \pm 0.7 \text{ km s}^{-1}$
$\text{N}(\text{CO})$	$\sim 7.0 \times 10^{16} \text{ cm}^{-2}$
$\text{N}(\text{NH}_3)$	$\sim 6.8 \times 10^{12} \text{ cm}^{-2}$
$\text{X}(\text{NH}_3)$	$\sim 1.0 \times 10^{-8}$
T_{rot}	$\sim 30 \text{ K}$

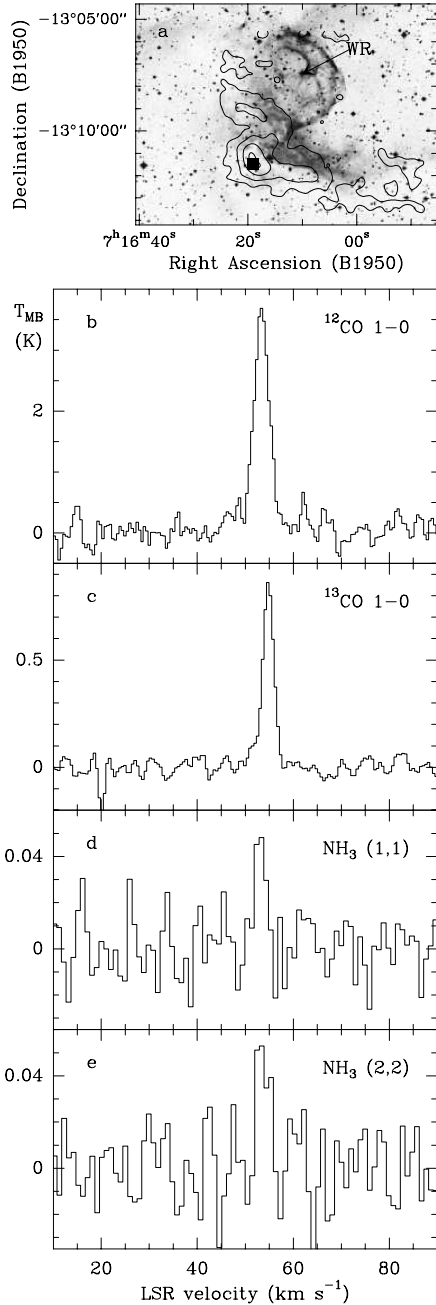


Fig. 1.— ^{12}CO , ^{13}CO and NH_3 emission toward the WR nebula NGC 2359. The intensity distribution map in a) corresponds to the CO $J = 2 \rightarrow 1$ emission (see Paper I). The individual profiles are from the black square plotted onto the clump to the southeast of the optical nebula. The position of the WN4 star HD 56925 is indicated by an arrow. In the profiles from b) to e), the molecular transition is indicated at the top right corner.

Assuming optically thin emission for both ammonia lines, we have derived the (1,1) and (2,2) column densities given in Table 1. From the ratio of the (1,1) and (2,2) column densities we estimate a rotational temperature of 30 K. Under typical conditions of the molecular gas, this rotational temperature can be considered as a lower limit to the kinetic temperature of the gas (Walmley & Ungerechts 1983). Using a kinetic temperature of 30 K and considering only the five lowest metastable ($J = K$) levels for the partition function, we derive a lower limit to the total ammonia column density of $7 \times 10^{12} \text{ cm}^{-2}$. For a CO column density of $0.7 \times 10^{17} \text{ cm}^{-2}$ (paper I) and assuming a fractional CO abundance of 10^{-4} , we derive a NH_3 abundance of $1 \pm 0.4 \times 10^{-8}$. This NH_3 abundance is comparable to those measured in cold galactic molecular clouds (Benson & Myers 1983) and shocked regions (Martín-Pintado & Cernicharo 1987; Tafalla & Bachiller 1995), but significantly higher than in PDR's (Fuente et al. 1990).

3. Discussion

The broad widths and the radial velocities of the (1,1) and (2,2) NH_3 lines indicate that the NH_3 emission arises from the gas which is interacting with the WR nebula. Two different kinds of interaction between an evolved massive star and the surrounding material are expected: UV photodissociation and shocks produced by the stellar wind. It is well known that the UV radiation from hot stars dissociates fragile molecules, such as NH_3 , even up to visual extinctions of 5 mag (i.e., H_2 column densities of $5 \times 10^{21} \text{ cm}^{-2}$). In this case, the photodissociation rate would be of the order of 10^{-7} s^{-1} (van Dishoeck 1988). Hence, the relatively high NH_3 abundance is striking in view of the rather low H_2 column density of $\sim 10^{21} \text{ cm}^{-2}$ derived from the CO data. If the total extinction between the star and the NH_3 region would be comparable to the total extinction derived from the CO data, the NH_3 must be produced very efficiently in order to compete with its photodissociation due to the WR star radiation field. From the dust continuum emission measured by the IRAS HiRes data at $60\mu\text{m}$ and $100\mu\text{m}$ (Aumann, Fowler & Melnyk 1990; J. R. Rizzo et al., in preparation), we have derived a dust temperature of 29 K and a column density in the range

$2 - 5 \times 10^{16} \text{ cm}^{-2}$ towards the position where NH_3 is detected. These values were obtained from the color-corrected $60\mu\text{m}$ and $100\mu\text{m}$ emission maps smoothed to an angular resolution of $2'$, and assuming an emissivity proportional to λ^{-2} . The dust grains were assumed to be spherical of size $0.1\mu\text{m}$ and with a density of 3 g cm^{-3} (Hildebrand 1983). Assuming the standard gas-to-dust ratio of 100, the total gas column density associated to the warm dust at 29 K is only 10^{18} cm^{-2} , at least two orders of magnitude below the total gas column density derived from CO in paper I. This suggests that basically all the dust associated with the molecular gas can not have temperatures of $\geq 10 \text{ K}$. The warm dust component measured by IRAS is likely associated to the material affected by the UV radiation from the WR star, shielding the warm gas from dissociation. The gas in the broad component seems to be warmer than the dust.

The presence of shockfronts acting in this region could explain both the NH_3 abundance and the gas kinetic temperature higher than the dust temperature in the broad component. A C-shock of $10\text{--}15 \text{ km s}^{-1}$ would heat the gas up to the temperatures derived from our data and release the NH_3 from the dust grain icy mantles (Flower & Pineau-Des-Forets 1994) to achieve the observed abundance. García-Segura & Mac Low (1995a, 1995b) have modelled the dynamical evolution of WR bubbles and predicted the presence of several shockfronts running into the surrounding gas at the different stages of the evolution of massive stars. When the WR stellar wind shocks the previous RSG ejecta, an expansion velocity of $\sim 10\text{--}15 \text{ km s}^{-1}$ is expected for the shocked gas. This velocity is in good agreement with the velocity separation of $12\text{--}13 \text{ km s}^{-1}$ measured between the shocked and the quiescent gas (paper I).

The Galactic center region (GC) is known to contain large amounts of warm gas with relatively high abundance of molecules like NH_3 , SiO and $\text{C}_2\text{H}_5\text{OH}$ extended over relatively large regions (Hüttemeister et al. 1995; Martín-Pintado et al. 1997; Martín-Pintado et al. 2001). This warm gas seems to be associated with the cold dust, and a shock chemistry has been claimed to explain the heating, the abundances and the densities of these molecules in the GC. However, the origin of the widespread shocks is, so far, unknown. Martín-

Pintado et al. (1999) have recently found that a large fraction of the hot NH_3 in the Sgr B2 envelope is located in shells of $1\text{--}2 \text{ pc}$, expanding at $8\text{--}10 \text{ km s}^{-1}$. The large NH_3 abundance and the rather high kinetic temperature found in the Sgr B2 envelope can be explained in terms of a C-shock chemistry (Flower, Pineau Des Forets & Walmsley 1995). Martín-Pintado et al. (1999) proposed that these hot molecular shells are the shocked layers produced by the strong winds of WR stars in the Galactic Center. The detection of warm NH_3 associated with the expanding shells produced by a WR stellar wind supports the possible origin for the warm NH_3 in the Sgr B2 envelope. Although the densities in the GC clouds are certainly higher than the density in NGC 2359, the ammonia abundances and the expansion velocities in the GC shells are comparable to those found in NGC 2359.

Hot ammonia has also been observed in the nuclei of the external galaxies IC 342 (Martin & Ho 1986; Ho et al. 1990) and Maffei 2 (Henkel et al. 2000; Takano et al. 2000). The rotational temperatures of 50 K and 80 K for IC 342 and Maffei 2, respectively, are similar to those observed in the GC. In both galaxy nuclei, the derived NH_3 abundances are also similar to the GC. Furthermore, the gas temperatures derived from NH_3 are higher than the dust temperature and the nucleus of IC 342 has overall properties similar to those of the GC region (Downes et al. 1992). In both galactic nuclei, IC 342 and Maffei 2, the gas heating is not due to recently formed stars but to large scale shocks. As in the case of the GC, the origin of such shocks remains unknown. Based on high angular resolution data ($5''$) from the nucleus of IC 342, Ho et al. (1990) conclude that the morphology of the NH_3 emission may be a distributed bump of small and hot molecular clouds surrounding young OB stars. However, the NH_3 is hard to be heated by the OB field radiation since it is easily photodissociated by the UV photons. It is worth noting that this ammonia distribution would also be consistent with hot shells like those observed by Martín-Pintado et al. (1999) in the GC. Further studies of the chemistry, physical conditions and kinematics of the molecular gas in the environs of galactic evolved massive stars would provide invaluable constraints to the models for the impact of the evolution of massive stars onto the interstellar medium.

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